CENTER FOR RADIOPHYSICS AND SPACE RESEARCH
CORNELL UNIVERSITY
ITHACA, NEW YORK

April 1963

CRSR 140

STRUCTURE OF THE MOON'S SURFACE*

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* Work on the constitution of the lunar surface is carried out at Cornell University under the National Aeronautics and Space Administration Grant NsG-382.

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(Paper presented at the American Geophysical Union, April, 1963)

by

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Investigations of the moon's surface have led many authors to conclude that a structure of high porosity forms the actual surface. Such information has come independently from thermal, radio thermal, radar and optical evidence. Some authors have concluded that a porous material was the consequence of volcanic activity making rock foams, while other authors had thought in terms of surface vaporization and condensation processes, brought about by micrometeorites (for example Sytinskaya in the USSR). Several authors argued that since the material was so much less dense than rock or sand, there was no possibility that the principal constituent was a finely divided rock powder. This argument is now seen to be incorrect and, on the contrary, properties of fine powders seem to fit the circumstances best.

It is not at all easy to guess about the properties of fine powders and experimental work is needed to gain an understanding. Many experiments with rock powders both in vacuum and in gases have been carried out in our laboratories at Cornell, and you have heard from Dr. Hapke who is mostly responsible for these, what extraordinary packing properties fine dust seems to possess. It has become clear that not only is it possible to have fine dust packed so that it is underdense by a factor between 6 and 10, but indeed this is quite common for small particles deposited in a great variety of ways. The packing into "fairy castles" results whenever individual particles are brought to the surface at a low enough speed, and when the particles are small enough so that the slight adhesive forces on contact are enough to maintain a particle in place on first contact. The action of micrometeorites on the moon's surface will assure just that. Each incoming high speed micrometeorite will hit the surface and generate a small puff of gas. This puff will eject a few particles at a high speed but many more particles will be dislodged and moved a short distance. The great majority of particles were thus last deposited at the positions where they are now lying from a small jump. In the case of the low lunar surface gravity and of the much greater adhesion that highly outgassed particles may possess, a much greater range of jumps will still result in a fairy castle structure than would in most laboratory experiments. If electrostatic forces occasionally prevent a particle from settling back on the surface and allow it to be transported further, as I have suggested in the past, then this will only assist in diminishing the velocity at impact and therefore enhance the tendency to fairy castle packing.

The moon's optical scattering law is extreme in two respects, compared with all the very many surfaces that have been tested. It is extreme for the strength of the backscatter compared with the scatter into any other direction, and it is extreme for the accurate independence of the scattering function on the angle that the surface makes to the directions of the incoming and outgoing light (leaving of course the very strong dependence on the angle between those two rays). As Dr. Hapke has shown, these properties are matched very accurately by any fairy castle packing of a powder that is dark enough to have the correct albedo and whose particles are sufficiently opaque. Even the most porous rock foams do not go far enough with respect to these two extreme properties; especially the complete independence on the angle that the surface makes to the rays of light cannot be achieved by a surface structure whose shadow-casting properties are minimal at normal incidence, and for any foam whose surface consists of open bubbles, this is indeed the case. The only materials that would satisfy the optical reflexion law other than the fairy castle packing would be materials that are very fibrous (we are leaving out of this discussion surfaces that require optical perfection, like glass spheres or corner reflectors since etching by micrometeorites would quickly destroy the surface properties).

It is important to emphasize that the optical reflexion law applies to every part of the moon's surface. There are slight differences, such that the backscatter peak is a little more intense for the ray material than for the maria, but these are comparatively small effects only and no presently discernible part of the moon's surface has scattering properties that approximate those of bare rock. Thus, if a lava produced underdense surface were proposed, it would be necessary to suppose that it covered every part, not only the maria but all the highlands, including the crater rims, and even the rims of the most recent craters that can be seen. This would seem implausible anyway, but it would certainly not be in accord with the widely accepted theory that the craters are mostly due to impact explosions. An explosion that leaves a pit of many kilometers diameter exerts pressures on the material that are reckonned in megabars, and the result is invariably completely compacted material, but torn up into rough shapes by the turbulence in the explosion. No crater on the moon's surface has optical scattering properties compatible with such a treatment, no matter what the original structure of the rock may have been. How are these facts to be reconciled?

There seems no possibility but to suppose that a surface action has taken place everywhere, which even in the youngest of the explosion craters has already gone far enough to fluff up a surface layer to the required underdense structure. Micrometeorites may do this in the manner discussed above.

This is where the discussion would stand were it not for the discovery by Pettengill of the intense radar scattering property of the crater Tycho. A range and Doppler shift analysis of the returned signal at 400 Mc/s has enabled Pettengill to pinpoint reflecting areas even smaller than the crater Tycho, and to recognize that a very large signal return came in fact all from the interior of that crater.

The one respect in which the crater is obviously outstanding is that is is in the class of the youngest features that can be recognized on the moon's surface. The extensive ray pattern associated with Tycho is itself an indication of the youth, for rays are always only associated with craters that are not overlapped by any other features. So far as can be judged, the rays of Tycho are not overlapped by anything else, and the rim of the crater is extremely neat and sharp compared with almost any other crater of similar size. For these reasons all authors are agreed in regarding Tycho as the youngest or one of the youngest craters of comparable size. In other respects the crater does not seem extraordinary, and there is no hint that it is different for any reason other than its youth. The optical properties are similar to the rest of the moon, but the thermal properties, as was shown by Shorthill, *et al*. 1960, and by Sinton, also show a remarkable anomaly. While the cooling curves obtained for most areas of the moon are accounted for by a very small value of the thermal diffusivity, much less than that of any bare rock, the crater Tycho displays a value which is not far from that of rocks.

The implication of these results is that at the depth relevant for the radar reflexion and for the thermal properties, the crater Tycho is much more similar to solid rock than most of the other surface, but that a very thin layer of underdense material exists there also, thick enough to determine the optical properties but too thin to determine the thermal or radar properties. For rock powders in fairy castle packing, the thickness effective for optical properties is of the order of a millimeter, for the thermal properties that have been investigated it is of the order of centimeters, and for the radio reflexion properties it is of the order of meters.

The huge explosion would have left a hard and rough surface whose radar scattering and thermal properties would be estimated to be quite similar to those that are in fact observed; it is all the other craters that pose a difficulty, for their radar reflexion is so very much less than would be obtained for explosion pits in rock and they must therefore be thought of as being much smoother on the scale of the wavelength (70 cm.) so as to scatter little power into the backward direction and to be composed of a more radar absorbent material than most solid rocks. It is all other craters that must therefore have been modified after they were made and their surfaces must have been smoothed over and made more radar absorbent. The thermal properties equally must have undergone a change so as to lower the value of the thermal diffusivity to that now observed for most of the moon's surface and leave only the youngest craters with a high value that is more nearly compatible with solid rock.

If most craters have had a similar history, we have to suppose that they also had a dense surface initially, which was first covered by a surface layer of a fluffy material. As time went on they would have become smoother and more absorbent to radio waves and the fluffy surface layer would have to grow to greater depths so as to approximate to the thermal characteristics of the majority of the moon's surface. It is very hard to see how any such action could have come from underneath, for it is not only the smoothness of the crater floor and its thermal diffusivity that is at stake but also of the crater walls. A mere filling in, as has been discussed in terms of the lava interpretation would not suffice. Throughout this process the optical surface layer must have retained the usual characteristics.

What can be said about the depth to which the surface must have become modified? Firstly, it must have been modified to a depth of centimeters to account for the thermal properties. Then, it must have been modified to a depth of meters in order to diminish the radar reflectivity to the average value of the moon, which is much less than that of any solid rock. Only very specially chosen material constants could achieve that in a depth of less than several meters. Thirdly, the treatment must have modified the surface to the depth equal to the scale of the initial roughness, which again from the radar evidence must have been on the scale of meters, and from evidence of big explosions, on a scale more like tens of meters. A process of erosion, of filling in of low spots and of covering over with deposited material seems to be required where this covering cannot be on a scale of much less than tens of meters. Seeing that craters are of different ages and all but the very youngest have been converted into the radar smooth and absorbent condition, it would not be reasonable to think that the process had only gone just far enough to achieve this in each one of them. It seems more likely that in most craters the depth of the surface treatment would be several times the minimum required to account for the data.

It is not possible at present to define the mechanical properties of such a deposit very closely. In a low spot the accumulation, as everywhere else, must always have been underdense on the surface, but it will no doubt be compacted at some depth. If all material were only gently deposited on the surface, and no other forces than gravity were at work, the material would only be compacted by its overlying weight and an extremely crushable structure would result resembling that of deep dry snow. It could well be, however, that the action of micrometerorites, as well as other agencies that are at work, tend to consolidate the underlying layers to a greater extent while still giving at all stages the very low density at the surface. A deep deposit, fluffy on top but stronger from a shallow depth onwards would then result. The amount of such compaction that would result from micrometeorites depends critically on the size distribution, which, even if it were known for the present, is not known for the history of the moon.

Compaction by the agencies that are most common on the earth would, of course, be absent on the moon. The present discussion implies that the filler material was always underdense at the top surface during the filling-in process, and it is, therefore, indeed a question of finding the most effective subsequent compaction process; one could not suppose that the filling-in process generated a dense material in the first place. With that understanding of the compaction processes, one has therefore to be prepared to find a crushable surface material many meters deep.

Since these considerations lead us to rather remarkable conclusions, let us examine the assumptions in more detail. At what point could the case have been argued differently?

1. The crater Tycho might be intrinsically of a different kind from all the others. Since its radar and thermal properties fit an explosion pit while those of the older craters do not, this would then imply that only Tycho and perhaps a few other young craters were caused by impact explosions and all the great number of older craters were generated in some other way.

2. One might suppose that a volcanic process filled over all the older craters but that this process was no longer active after the event of Tycho. In that case, one would need to suppose that volcanic action caused not only the crater bottoms but also the rims to be covered with a material of much lower radar reflectivity than the bare rock left after the explosions, and that again means a covering of several meters' depth. Lava flows producing rock foam might have been considered for the crater bottoms but could hardly be considered to have made a covering over all the crater rims. The optical properties of the surface could not be attributed to such a volcanic action since they have to be matched by the crater Tycho which has not suffered any such modification.

3. The erosion and smoothing could be due mainly to larger impacts generating rubble rather than dust. This is possible, but a large amount of underdense material would still have to be generated

so as to account for the thermal properties which allow only a few percent of the moon's surface to be exposed rubble. At all stages in the breakup the majority of the surface would have to be covered with some centimeters of the fluffy material.

The generation of the fluffy surface material has to be thought of as connected with local processes on the surface rather than with a general blanketing by micrometrorites or by volcanic ash or by all the ray material ejected from all the craters. For in all the cases of general blanketing, no explanation would remain for the characteristic color differentiation whereby the high ground is generally lighter than the low ground. The conclusion that all ought to be the same color because it is the same material can be avoided if the underdense surface is generated at least in part from local stuff rather than from a general blanket.